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A PRELIMINARY STUDY OF HANDLING-QUALITIES REQUIREMENTS OF SUPERSONIC TRANSPORTS IN HIGH-SPEED CRUISING FLIGHT USING PILOTED SIMULATORS

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A PRELIMINARY STUDY OF HANDLING-QUALITIES REQUIREMENTS OF SUPERSONIC TRANSPORTS IN HIGH-SPEED CRUISING FLIGHT USING PILOTED SIMULATORS*

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SUMMARY

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Two different simulators were used in a piloted motion simulator study to obtain preliminary handling-qualities data on a supersonic transport in cruising flight at a Mach number of 3.0.

Results indicate that for configurations currently being considered for the supersonic transport, augmentation of the rotational damping characteristics is likely to be required around all three axes, the greatest increment being required for the yaw axis. The static stability characteristics, however, appear to require less augmentation than the damping characteristics. The problem of limiting the sideslip excursions following abrupt loss of thrust of an outboard podded engine contributed greatly to the requirements for directional damping and stability. The satisfactory handling-qualities characteristics defined for a transport airplane by this study differ from those defined in previous studies of fighter-type airplanes, and indicate a need for a separate appraisal of transport handling-qualities requirements. Accurate appraisal of the effects of large disturbances of the airplane requires simulator capabilities that reproduce translational as well as rotational motions.

INTRODUCTION

Performance considerations are leading to designs for the supersonic transport that differ in many important respects from those of airplanes currently flying. Preliminary estimates of the handling qualities associated with these designs (ref. 1) and wind-tunnel data (refs. 2 to 7) indicate that they will present some dynamic problems that require investigation. Accordingly, a piloted simulator study has been initiated at the Ames Research Center of the NASA to study the handling-qualities problems of the supersonic transport. The present report describes the results of preliminary motion-simulator studies of these problems in cruising flight. The purpose of the studies was not only to investigate the handling-qualities problems but also to define the motion-simulator sophistication required for such studies.

The present results have been related to the specific characteristics of a delta-wing canard configuration, primarily because reference data for this configuration were conveniently available. It should not, however, be inferred that the conclusions are uniquely applicable to this configuration. Most of the designs under consideration for the supersonic transport and, in fact, most of the configurations designed to cruise at Mach numbers up to 3.0 at extreme altitudes for any mission have elongated fuselages, low-aspect-ratio wings, and tail proportions that would produce aerodynamic damping derivatives of the order ascribed to the delta-wing canard configuration. From this standpoint, the results presented here may be considered generally applicable.

NOTATION

AR aspect ratio

b wing span, ft

c wing chord, ft

$\bar{c}$ wing mean aerodynamic chord, $\frac{\int c^2 dy}{\int c\ dy}$, ft

C_D drag coefficient, $\frac{\text{drag}}{\bar{q}S}$

C_{D_o} drag coefficient at zero lift

$C_{D_{C_L^2}}$ drag rise with lift, $\frac{\partial C_D}{\partial (C_L^2)}$

C_L lift coefficient, $\frac{\text{lift}}{\bar{q}S}$

C_{L_α} airplane lift-curve slope, $\frac{\partial C_L}{\partial \alpha}$

$C_{L_{\delta_e}}$ lift variation with elevator deflection, $\frac{\partial C_L}{\partial \delta_e}$

C_l rolling-moment coefficient, $\frac{\text{rolling moment}}{\bar{q}Sb}$

C_{l_p} roll due to rolling, $\frac{\partial C_l}{\partial (pb/2V)}$

C_{l_r}	roll due to yawing, $\frac{\partial C_l}{\partial(rb/2V)}$
C_{l_β}	effective dihedral derivative, $\frac{\partial C_l}{\partial\beta}$, per radian
$C_{l_{\dot\beta}}$	roll due to sideslip rate, $\frac{\partial C_l}{\partial(\dot\beta b/2V)}$
$C_{l_{\delta_a}}$	roll control power derivative, $\frac{\partial C_l}{\partial\delta_a}$, per radian
C_m	pitching-moment coefficient, $\frac{\text{pitching moment}}{\bar{q}S\bar{c}}$
C_{m_q}	pitch due to pitching velocity, $\frac{\partial C_m}{\partial(q\bar{c}/2V)}$
C_{m_α}	static longitudinal stability derivative, $\frac{\partial C_m}{\partial\alpha}$, per radian
$C_{m_{\dot\alpha}}$	pitch due to angle-of-attack rate, $\frac{\partial C_m}{\partial(\dot\alpha\bar{c}/2V)}$
$C_{m_{\delta_e}}$	pitch control power derivative, $\frac{\partial C_m}{\partial\delta_e}$, per radian
C_n	yawing-moment coefficient, $\frac{\text{yawing moment}}{\bar{q}Sb}$
C_{n_p}	yaw due to rolling, $\frac{\partial C_n}{\partial(pb/2V)}$
C_{n_r}	yaw due to yawing, $\frac{\partial C_n}{\partial(rb/2V)}$
C_{n_β}	static directional stability derivative, $\frac{\partial C_n}{\partial\beta}$, per radian
$C_{n_{\dot\beta}}$	yaw due to sideslip rate, $\frac{\partial C_n}{\partial(\dot\beta b/2V)}$
$C_{n_{\delta_a}}$	aileron yaw derivative, $\frac{\partial C_n}{\partial\delta_a}$, per radian
$C_{n_{\delta_r}}$	yaw control power derivative, $\frac{\partial C_n}{\partial\delta_r}$, per radian
C_Y	side-force coefficient, $\frac{\text{side force}}{\bar{q}S}$
C_{Y_β}	side-force derivative, $\frac{\partial C_Y}{\partial\beta}$, per radian
$C_{Y_{\delta_r}}$	side-force variation with rudder deflection, $\frac{\partial C_Y}{\partial\delta_r}$
F_s	longitudinal stick force, lb

g	acceleration due to gravity, 32.2 ft/sec^2
I_x, I_y, I_z	moments of inertia about the airplane X, Y, and Z axes, respectively, slug-ft^2
L_p	$\left(\frac{\bar{q}Sb}{I_x}\right)\left(\frac{b}{2V}\right)C_{l_p}$, per sec
L_{δ_a}	$\left(\frac{\bar{q}Sb}{I_x}\right)C_{l_{\delta_a}}$, per sec^2
M_{δ_e}	$\left(\frac{\bar{q}S\bar{c}}{I_y}\right)C_{m_{\delta_e}}$, per sec^2
P	period, sec
p	rolling velocity, radians/sec
PR	pilot rating
q	pitching velocity, radians/sec
$\bar{q}$	dynamic pressure, lb/ft^2
r	yawing velocity, radians/sec
S	wing area, sq ft
$T_{1/2}$	time required for oscillation to damp to half amplitude, sec
T_2	time required for oscillation to double amplitude, sec
V	velocity, ft/sec
W	airplane gross weight, lb
y	spanwise distance, normal to plane of symmetry, ft
y_e	distance from plane of symmetry to an outboard engine, ft
α	angle of attack, radians
$\dot{\alpha}$	time rate of change of angle of attack, radians/sec
β	sideslip angle, radians
$\dot{\beta}$	time rate of change of sideslip angle, radians/sec
δ_a	total aileron deflection, positive for right aileron trailing edge down, radians

δ_e elevator (canard) deflection, positive for trailing edge down, radians

δ_p deflection at top of control stick, in.

δ_r rudder deflection, positive for trailing edge left, radians

ζ longitudinal short-period damping ratio

ζ_d damping ratio of the Dutch roll oscillation

φ angle of bank

ω_d undamped natural frequency of the Dutch roll oscillation, radians/sec

ω_φ undamped natural frequency appearing in the numerator of the φ/δ_a transfer function, radians/sec

ω_n undamped longitudinal short-period frequency, radians/sec

SIMULATORS

Two ground-based simulators were used in the investigation: a three-degree-of-freedom simulator, which provided motion in roll, pitch, and yaw, and a five-degree-of-freedom simulator which added vertical and side translations to the rotational motions.

The three-degree-of-freedom simulator, designated hereafter for brevity as "the three-degree simulator" is shown in figure 1 with the canopy removed. In operation, an opaque canopy covered the cockpit so that instrument flight conditions were simulated. The motion limitations, as used in this program, were $\pm 90^\circ$ in roll, $\pm 40^\circ$ in pitch, and $\pm 70^\circ$ in yaw. For each of the modes, the dynamic response of the drive system was such that the natural frequency, as defined by a phase lag of 90°, was about 1 cycle per second, which was well above the frequencies involved in the simulation. The damping ratio was about 0.7. An instrument panel (fig. 2) included as basic flight information, airspeed, Mach number, altitude, a turn-and-bank indicator, a gyro horizon, a heading indicator, vertical acceleration, the rpm of two engines (the two outboard engines of an assumed four-engine configuration), angle of sideslip, angle of attack, and rate of climb.

The pilot controls included rudder pedals and, for convenience, a stick, in place of the usual transport wheel-type control. Two throttles governed the thrust of the two outboard engines; the thrust of the two inboard engines remained constant at the level required for cruise flight.

The five-degree-of-freedom simulator ("five-degree simulator") was constructed by mounting the three-degree simulator on the end of the arm of a centrifuge (fig. 3). With the cockpit erect and facing radially outward, motion up and down the vertical track provided vertical acceleration, and motions of the centrifuge arm provided side accelerations. The vertical travel was limited to

±1-3/4 feet and the frequency response of its drive system produced a phase lag of 90° at 2.2 cycles per second with a damping ratio of 0.7. For these tests the centrifuge arm travel was limited to a rate of 6 revolutions per minute, with a corresponding centrifugal acceleration at the cockpit of 3/8 g (centrifuge arm radius, 30 ft). The dynamic response of the centrifuge arm produced a phase lag of 90° at 0.8 cycle per second.

With the physical travel available on the five-degree simulator, it was not possible to provide an unmodified duplication of the airplane cockpit motions for all maneuvers. Washout, a term which describes drive signals that are superimposed on computer-developed signals to return the simulator to zero conditions at a relatively slow rate, was used to enable operations within practical displacements. The development of the washout system used in the test program is described in the appendix.

An analog computer was used in conjunction with both ground simulators to compute the response of the airplane to inputs supplied by the pilot. Six degrees of freedom were included in the equations of motion, which were referred to body axes; all aerodynamic derivatives were linearized and assumed constant at an average value over the angle-of-attack range.

TESTS

The physical characteristics assumed for the example airplane are shown in table I and the basic aerodynamic characteristics assumed are shown in table II. The static margin of the basic airplane at $M = 3.0$ was 9 percent. The complete damping derivatives ($C_{m_q} + C_{m_{\dot{\alpha}}}$, $C_{l_p} + C_{l_{\dot{\beta}}} \sin \alpha$, etc.) are given as they were measured in wind-tunnel dynamic model tests; however, for the example configuration the angle-of-attack rate and sideslip-rate terms were considered negligible and were not used in the simulation equations. Hereafter in the report, the damping derivatives are referred to as C_{m_q}, C_{l_p}, C_{l_r}, C_{n_p}, and C_{n_r}.

Since handling-qualities criteria for cruising flight of a supersonic transport have not been rigorously defined, the definition of evaluation tasks and criteria was treated as one of the objectives of the investigation, and to some extent, the pilots were allowed to use their own judgement in developing and applying test methods and criteria. In conducting the tests, the pilots used basic handling-qualities evaluation techniques that had been developed in previous flight handling-qualities programs (i.e., response to control pulses and steps, oscillatory characteristics following a disturbance, etc.). In addition, tasks were examined that were considered representative of transport piloting problems for cruising flight (i.e., ability to hold altitude precisely, ability to turn precisely, ability to initiate and hold specified rates of climb, and to level off with precision, etc.). An additional task supplied was that of controlling the effects of abrupt loss of thrust of one engine. As shown in reference 4, the yawing moments incident to this failure were much larger than would be calculated by simply multiplying the thrust loss by the appropriate moment arm; interference effects resulting from the shock wave expelled from the engine nacelle accounted for the increase in yawing moment noted in table II. Only the effects of total power failure of an outboard engine were simulated in this program.

The following is typical of the criteria assumed by one or more of the pilots for their evaluations:

1. Normal operation, pilots' ratings 1 to 3-1/2:[1]

   a. The airplane should be readily controllable with two controls only (i.e., rudder for coordination should not be required during normal operation).

   b. Sideslip angle of about 1° should not be exceeded during normal two-control operation.

   c. When thrust from a critical engine is lost abruptly, the resulting sideslip angle should not exceed 5° with no corrective rudder applied and with ailerons used to maintain wings-level flight.

2. Emergency operations, pilots' ratings 4 to 6-1/2:

   a. Use of rudder may be necessary to keep the sideslip angle within 1° in normal maneuvers.

   b. When thrust from a critical engine is lost abruptly, the resulting sideslip angle of 5° might be exceeded were it not for the application of corrective control. The degree of acceptability is determined by the rate of divergence, not only in sideslip but also in roll or pitch, and by the ease with which the motions can be controlled.

Only the derivatives that were considered of major importance were treated as variables in the simulator investigation. These were C_{m_α}, $C_{m_{\delta_e}}$, C_{m_q}, C_{l_p}, $C_{l_{\delta_a}}$, C_{l_β}, $C_{n_{\delta_r}}$, C_{n_β}, C_{n_r}, and $C_{n_{\delta_a}}$; the remaining stability derivatives were kept at the values for the basic airplane listed in table II. Control-force variations with cockpit-control deflection were kept constant at the values shown in table II; the gearings shown were arrived at during preliminary tests as a compromise of control sensitivity and control power required to control large disturbances of the airplane.

Five test pilots (four of them NASA) with varied experience in piloting large multi-engine airplanes performed the evaluations. Incidental evaluations were also obtained from several airline pilots; the time spent on these evaluations by the latter pilots was not considered enough to provide more than a rough corroboration of the results. All five of the pilots did not conduct evaluations on both simulators; the phases tested by each pilot are listed in table IV.

[1]The pilot rating schedule used in this program is shown in table III.

RESULTS AND DISCUSSION

The results obtained in this study are of interest from two standpoints: first, the indications of required aerodynamic levels of stability and damping for the airplane, with consideration of the effects of a stability augmenter failure, and second, the indications of what motion simulator sophistication is required in order to produce valid results. In the following sections, the results are presented and discussed in these respective terms. An additional section is included which was prompted by initial findings of the investigation that showed the basic airplane to be deficient in stability characteristics in a number of modes.

In order to establish a reasonable base configuration for subsequent evaluations of stability augmenter failures, the pilots were first given the task of defining the combination of satisfactory characteristics that would represent the fully augmented airplane. These results, obtained on the three-degree simulator, are discussed in the following section, followed by the results pertaining to failure of a stability augmenter.

Definition of a Satisfactory Airplane

The combination of values of derivatives selected by several pilots, independently, as "good" (PR 1-1/2) and "marginally satisfactory" (PR 3-1/2) according to the rating schedule of table III is indicated in table V. As shown, the agreement in the values selected by the different pilots is generally good. Some differences are evident in the values; in part, they result from the viewpoint of some of the pilots that subsequent evaluations would not be compromised if the augmented basic characteristics were very close to, but not quite optimum. Identical values selected for certain derivatives result from the particular discrete values available to the pilots during the simulator tests.

Comparison with handling-qualities criteria.- One of the basic goals of the long-range simulator program at Ames is to establish the handling-qualities requirements of the supersonic transport airplane. Since the present study serves as a first examination of such requirements, it is interesting and informative to compare the types of behavior selected here as "good" and "marginally satisfactory" with those determined in other investigations, although the criteria used for evaluation may not be comparable. Figure 4 shows these comparisons for a number of parameters. The plotted points represent the average values for four pilots for the good airplane (table V(a)) and for three pilots for the marginally satisfactory airplane (table V(b)). The results are consistent with predictions that might be made intuitively in that, generally, slower responses were found to be allowable for the supersonic transport than would be inferred from the boundaries of figure 4. This appears reasonable since these boundaries resulted from flight and simulator studies involving fighters or other small airplanes having maneuvering requirements dictated by military needs. Thus, in figure 4(a), the frequencies and dampings selected for the supersonic transport airplane place the vehicle in an area that would be sluggish for a fighter airplane according to boundaries from reference 8.

Table V indicates that less static stability generally was desired for the good airplane (PR 1-1/2) than for the marginally satisfactory airplane (PR 3-1/2). This probably results from the longitudinal control effectiveness and stick force per unit stick deflection being retained at a constant level, which produced a stick-force gradient of 14 pounds per g for the good airplane, compared with 27 pounds per g for the marginally satisfactory airplane. A stick-force gradient of 27 pounds per g is excessive for fighters (see ref. 9), but even with a stick control it was thought to be acceptable for a transport because of the lower acceleration limits of the transports. However, while stick-force and elevator control-effectiveness characteristics were not in themselves under evaluation, it appears that the large increase in stick force per g and the associated decrease in control power at higher static stability were interpreted by the pilots as a reduction in airplane response which apparently affected their ratings. Requirements for holding altitude precisely played a large part in arriving at these particular ratings, because the rate of climb varies rapidly with flight-path angle at the high airspeeds considered and is, therefore, correspondingly sensitive to attitude.

Short-period lateral-directional requirements are compared in figure 4(b), with boundaries established for airplanes in the landing approach, as derived in modified form from reference 10. The results are consistent, reflecting a parallel requirement for good controls-fixed stabilization of this mode. Figure 4(c) shows a relaxation of aileron control power requirements as compared with those for fighter-type airplanes (ref. 11), which is not surprising in view of the relative maneuvering requirements of the two classes of vehicles.

In figure 4(d) are shown boundaries that define allowable aileron control cross-coupling effect as developed in reference 12. Data from the present program confirm the fact that minimal cross-coupling effect is desired for the supersonic transport.

For lack of more appropriate data the foregoing comparisons were based on criteria developed largely for use with fighter-type airplanes. It should, perhaps, have been anticipated that the comparisons would show that some handling-qualities criteria developed for fighter-type airplanes would penalize the design of a supersonic transport, if applied directly. Additional effort should, therefore, be made to develop specifications more appropriate to the supersonic transport.

Effects of Inoperative Stability Augmenter

The results of tests to evaluate the effects of an inoperative stability augmenter are shown in figures 5, 6, and 7 in the form of pilot ratings as functions of the various derivatives. The basic airplane values of the derivatives are indicated. In each test, the general procedure was to supply the augmented derivatives for the good airplane (PR 1-1/2), as selected by the particular pilot, and from this base level one of the derivatives was adjusted to different values and the resulting combination was evaluated. It should be noted that these conditions were rated on the basis of an inoperative stability augmenter, not normal airplane characteristics. Independent ratings were obtained for normal operations and for the task of controlling for a sudden loss in engine thrust, primarily to gain an insight into the order of importance of the latter problem. In operations of the three-degree simulator, the differences in rating for the two criteria were small, ranging from 0 to 1 pilot rating unit. In operations of the five-degree simulator, the differences were also small except for the derivatives associated with the primary responses to engine failure, as noted subsequently. The ratings shown in figures 5, 6, and 7 are the more pessimistic ones that apply to an engine failure, since it proved to be the most critical condition.

Yaw damping derivative, C_{n_r}.- The results obtained for the yaw damping derivative C_{n_r} are shown in figure 5(a). As can be seen by reference to the unaugmented value for the basic airplane, the required value of the derivative for a good airplane (PR 1-1/2) is considerably greater than the basic value. This derivative proved to be by far the most deficient, requiring nearly 15 times the basic value in order to achieve a pilot rating of 1-1/2. Even for a marginally satisfactory pilot rating of 3-1/2, the basic value of C_{n_r} would have to be increased approximately 5 times.

Differences are seen in the general level of the C_{n_r} data points obtained from each simulator which are related to the differences in evaluation tasks. The evaluations from the five-degree simulator generally showed a less favorable rating for a given value of C_{n_r} than did the data from the three-degree simulator. These differences resulted primarily from consideration of the effects of abrupt loss of thrust of an engine; for normal operations the five-degree simulator results agreed with those from the other simulator. The pilots commented that the poorer ratings from the five-degree simulator for the engine-failure conditions resulted from the magnitude of the side acceleration motions at the pilot compartment. These motions, which were initially reproduced quite faithfully in the five-degree simulator (fig. 8), could only be inferred on the other simulator, where only the rotational motions could be accurately reproduced. Thus, although the pilots were advised beforehand that translational motions would not be accurately reproduced during operation of the three-degree simulator, it appears that they were unable to project accurately the sensations that should have been produced, and accordingly, rated the configurations optimistically.

Further comment should be noted on the subject of pilot differences. One pilot did not rate these configurations poorer on the five-degree simulator. He observed, in agreement with the other pilots, that the side motions were objectionable as such, but noted that they provided at the same time a valuable cue for instinctive application of corrective rudder control to limit the sideslip excursion. Further, it was indicated, if these added motions were too small to be detected, or small enough to be obscured by atmospheric turbulence or buffeting, a valuable clue for corrective action to limit sideslip would be lost. A similar observation had been made by another pilot with respect to dihedral effect; too little dihedral effect deprived the pilot of a valuable clue to the development of sideslip angle. It is apparent from these and other observations that the relatively low limiting sideslip angle of 5° used as an evaluation criterion strongly influenced the pilot ratings. Detection of sideslip angle by the pilot in the absence of aerodynamic clues is a difficult task, since this information is not absorbed easily and rapidly from most instrument displays. When it is a critical factor, as in the present investigation, the pilot must develop alternative sources of information, and a compromise must be reached between motions that are strong enough to serve as clues and motions that are strong enough to represent additional control problems. It does not seem unreasonable to speculate that some of the differences observed in ratings from different pilots in this study are due to diverse preferences for source or strength of sideslip information clues. Such differences in viewpoints are, of course, not uncommon in pilot evaluations, particularly for marginally satisfactory situations.

Roll and pitch damping derivatives, C_{l_p} and C_{m_q}.- Some augmentation is indicated to be needed for the roll and pitch damping derivatives C_{l_p} and C_{m_q} (figs. 5(b) and 5(c)), although the amounts are less than those for the yaw damping derivatives. For a PR of 1-1/2, augmentation to about 5 and 4 times the basic value, respectively, is indicated, and for a PR of 3-1/2, about 2-1/2 and 2 times. No differences in the ratings were indicated from tests on different simulators or from consideration of the effects of abrupt loss of engine thrust. As regards the value of C_{m_q}, this is not surprising in view of the fact that the translational motions in the pitch plane were not severe as a result of abrupt engine thrust loss or normal maneuvers, and the limited vertical travel available severely restricted the motion reproduction capabilities of the five-degree simulator. Similarly, regarding the value of C_{l_p}, little difference should have been expected with different simulators because of the generally low level of roll excitation that accompanied an engine failure.

Static stability derivatives.- In general, the static stability derivatives (fig. 6) did not show the consistent requirements for augmentation that were noted for the damping derivatives. The curves for C_{m_α} indicate that the value of this derivative for the basic airplane falls in a satisfactory range. In contrast with the clearly defined ratings observed for the damping derivatives, the data for C_{n_β} and C_{l_β} exhibit considerable scatter, which could not be reduced by closer definition of the evaluation tasks. The spread of values is so large that while average values would indicate the basic airplane values for these derivatives to be satisfactory, pessimistic values would indicate them to be unsatisfactory, and hence, to require augmentation. Thus, additional work needs to be done to define satisfactory levels for these derivatives. One fact is noteworthy with regard to the values of C_{n_β}; as tested on the five-degree simulator, the ratings were poorer than those defined in three-degree simulator operation. Here, as with the related derivative C_{n_r}, the side motions following loss of an engine influenced the ratings strongly. Since they were reproduced on the five-degree simulator, the ratings obtained there are considered more reliable.

Aileron yaw derivative, $C_{n_{\delta_a}}$.- The data in figure 7 show that zero aileron yaw, which minimizes cross-coupling effects of the control, was desired by all pilots. Ratings deteriorated rapidly with increasing aileron yaw of either positive or negative sign. The rate of deterioration was nearly the same for both positive and negative values; however, adverse aileron yaw was rated somewhat worse because ailerons used to hold the wings level following an engine failure produced yawing moments that augmented those due to the engine failure.

Effects of multiple failures of stability augmenters.- It is noteworthy that, in general, the ratings developed in this study are strongly dependent on the values assigned to derivatives other than those varied. Thus, the values plotted in figures 5, 6, and 7 are, strictly speaking, appropriate only with all other derivatives at completely satisfactory levels (PR 1-1/2). This limitation of the data was demonstrated forcibly by some incidental tests in which the values of derivatives that were individually rated 3-1/2 were tested in combination. The resulting configuration was rated at 6-1/2 to 7, definitely unacceptable. Certain subgroupings of derivatives can also be identified which are intimately related, and which should be considered in combination in further studies in this area. Static stability and damping in the pitch mode, and aileron yaw and dihedral effect are groupings that would merit attention for the particular problem of the supersonic transport. Cross-coupling effects introduced by such terms as C_{n_p}, C_{l_r}, and fuselage inclination also appear to be worthy of examination for unusual supersonic transport configurations.

Transient effects of stability augmenter failures.- Most of the tests conducted in the present program considered only the long-term effects of a stability augmenter failure; that is, it was assumed that the combination of derivatives being evaluated had existed for some time. A limited number of tests were also conducted on the five-degree simulator in which a value for a derivative was changed suddenly, and without warning, to a poorer level during routine maneuvers. This situation had been shown in reference 13 to result in complete loss of control in some cases where the pilot was engaged in a task requiring tight control of the airplane. In the present tests no particular difficulties were experienced, and it is surmised that routine airline maneuvers simply do not require the tight control that led to trouble in the tests of reference 13. No "hard-over" stability augmenter failures were included in the test program.

Application of the Results

Two assumptions regarding test conditions for this study merit some discussion in relation to interpretation of the quantitative results. The values of I_X, I_Y, and I_Z selected for the configuration are representative values which can be refined only when the final configuration is more firmly established. Since the primary problems indicated by the study are associated with motions in the yaw mode, the values of I_Z, in particular, should be compared carefully in applying the data to other configurations.

Similarly, the limiting sideslip angle of 5° used in these studies, particularly for the problem of abrupt loss of thrust from an engine, may be considered as somewhat arbitrary. Although it was selected primarily as a reasonable structural design value for the vertical tail, it was also considered as possibly introducing limitations due to air-flow asymmetries or flow disturbances in the inlets of the operating engines, which could increase the severity of the problem. At present, there does not appear to be sufficient information on hand with which to refine the limiting sideslip angle or possible secondary effects, but the basis for these assumptions should be kept in mind for reappraisal of the results as more refined data become available.

There has been considerable discussion during this program relating to the problem of controlling for the effects of abrupt loss of thrust of an engine.

Ideally, the airplane should be designed so that sideslip excursions following failure of the engine remain within satisfactory limits with no corrective control application, and the airplane rated 1-1/2 satisfied this criterion. A less rigorous requirement based on the use of corrective control by the pilot would reduce the stability augmentation requirements, and this raises the question of how much alertness and effort can be expected of the pilot. The problem arises, of course, only after an augmenter has failed. Perhaps it can be presumed that the pilot would be aware of the augmenter failure, and knowing the consequences of a succeeding engine failure, would remain poised to provide corrective control, at least until a safer flight condition had been established. In the present study, the pilots were requested to consider the problem from this aspect and from the aspect of the additional distracting workload that could be presumed to exist in actual operations. The results should then include the effects of such considerations as best they could be visualized by the pilots, but the simulation was admittedly deficient in supplying a realistic environment; the study was frankly slanted heavily toward examination of the effects of an engine loss, and the pilots were accordingly more alert to control for it. (It may be questioned whether any simulation of this kind could realistically reproduce the live operational conditions in a form that would eliminate this artificial alertness.) Under these circumstances, the validity of the results is probably best indicated by the consistency of data obtained from different pilots, each of whom might have applied the alertness factor to a different degree, and from this standpoint, the results appear encouragingly consistent.

In the preceding discussion it was suggested that intensive alertness might be required for only a limited time. In this connection it should be noted that the pilot rating of 6-1/2 has been interpreted as defining a condition that the pilot could control for a time interval after the failure occurred, during which the Mach number (and altitude) could be reduced to a region where the normal additional aerodynamic damping would be adequate. Using experimental variations of derivative values with Mach number presented in reference 2, some estimates have been made of the Mach number that would be necessary to provide aerodynamic damping derivatives that would rate 3-1/2. To define the associated altitude, it was assumed that the value of C_L for (L/D maximum) remained the same with changing Mach number. These calculations indicate that for C_{l_p} and C_{m_q}, the Mach number would have to be reduced from 3.0 to 2.1 (and the altitude from 70,000 to 53,000 feet), and for C_{n_r}, the Mach number would have to be reduced to 1.5 (and the altitude to 37,000 feet). If the airplane could be certified on the basis of this approach, then the aerodynamic damping requirements might be relaxed by designing so that some common Mach number and altitude would serve for any single damping augmenter failure. The value of this approach would need to be examined further in terms of whether the mission could be completed satisfactorily from a performance standpoint at these adjusted flight conditions.

Passengers seated at the front end of the cabin will be subjected to motions similar to those of the pilot compartment, and several individuals were asked, as seated passengers, to evaluate the motions following an engine failure. It does not appear that these motions are substantially worse than those experienced in turbulence in current transports and therefore no new problems affecting passenger safety are indicated.

CONCLUSIONS

Two different simulators have been used in a piloted motion simulator study of the handling qualities of a supersonic transport in cruising flight at a Mach number of 3. The following conclusions have been reached:

1. For configurations currently being considered for the supersonic transport, augmentation of the rotational damping characteristics is likely to be required around all three axes. The static stability characteristics appear to require less augmentation than the damping characteristics.

2. The problem of limiting the sideslip excursions following abrupt loss of thrust of an outboard podded engine contributes greatly to the requirements for directional damping and stability.

3. Comparisons between satisfactory characteristics defined for a transport airplane by this study and those defined in previous studies for fighter-type airplanes emphasize the differences in mission requirements of the two airplane types and indicate a need for separate appraisal of transport handling-qualities requirements.

4. Accurate evaluation of the effects of large disturbances of the airplane requires simulator capabilities that reproduce translational as well as rotational motions. Limitations in the reproduction of translational motions were found that appear to present problems with any practical motion simulator design.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Nov. 27, 1962

APPENDIX

MOTION SIMULATION WITH A FIVE-DEGREE-OF-FREEDOM MOTION SIMULATOR

The investigation reported here represents one of the first known attempts to simulate handling-qualities problems around a 1 g base level with a five-degree-of-freedom motion simulator oriented as described. As mentioned earlier, difficulties were experienced in developing satisfactory arrangements for limiting the motion of the simulator. Because these difficulties were not completely resolved during the program, they may have influenced the pilots' evaluations to some degree. Also, some rather fundamental problems associated with such motion simulations were illuminated, and for these reasons it appears worthwhile to review the problems.

Basically, of course, the purpose of a motion simulator is to supply kinesthetic cues to enable the pilot to appreciate the control handling-qualities problems more realistically. It has been fairly well established that only the accelerations of the motions are sensed by the pilot. Thus, the approach taken is to try to apply realistic accelerations where they contribute to the handling, and to wash out these accelerations slowly, so that the pilot is unaware of, or at least unaffected by, the washout. This is done in such a way that the oscillatory motions of interest remain unmodified.

In the present program there appeared to be little cross coupling of longitudinal and lateral-directional problems so that it is possible to discuss them separately.

For the longitudinal motion, fairly strong washouts were required for the vertical travel because of the limited motion available - 3-1/2 feet. In the evaluation tasks considered (controlling a poorly damped airplane, holding altitude, initiating climbs, and leveling off, etc.), this motion, in conjunction with pitching rotation that was comparably washed out, contributed significantly to the realism of the "feel," although the longitudinal motion did not seem to be required for evaluation.

The main difficulties centered around the lateral-directional motions. As already noted, the cab orientation was selected to enable side accelerations to be represented by motion of the cab around the circular track. (The scheme of using cab bank angle to supply high-frequency side accelerations through orientation of the gravity vector was discarded after a quick appraisal, because the rapid changes in side acceleration occasioned by asymmetric thrust losses, for example, produced roll motions that could not be differentiated from aerodynamic roll motions.) In theory, this arrangement permits side accelerations (or at least the component of side acceleration represented by motion around the track) to be sustained until limiting arm velocities are reached. In practice it was found that the large velocities attained with sustained accelerations became apparent to the pilot through the noise levels, the centrifugal acceleration (0.37 g at limiting velocity), and possibly other factors, tending to obscure the acceleration cues that were of primary interest.

These effects, in some cases, contributed to nausea of the pilot. Some washout of the motion around the track was, therefore, necessary. The degree of washout required appeared to be somewhat a function of the particular task being evaluated. A strong washout was desired to minimize the discomforting effects of large velocities around the track, and seemed to be acceptable for the higher frequency oscillations ($P \approx 4.5$ sec). With low frequency motions ($P \approx 12$ sec), however, the strong washout damped out the cab motions at an apparent frequency different from the airplane frequency as evidenced by flight instruments, and for this case the cab motions were considered actually detrimental by some pilots. A solution to this problem was to apply bank angle for gravity orientation to replace the accelerations canceled by the washout introduced on the arm motion. If a moderate arm washout were applied, which permitted moderate motions around the track, the necessary bank angles would be applied at a relatively low frequency or roll rate so that they might remain undetected by the pilot. No arrangement could be found that was completely satisfactory in reproducing side accelerations accurately; in oscillations, the pilot sensed the roll motions as an apparent negative dihedral effect. A final solution, it appears, may require adjustment of the washout arrangement for the particular task, and in all likelihood, acceptance of accelerations which, though erroneous in magnitude, still vary in proper phase with the correct accelerations. The limitations described here, it will be noted, do not arise peculiarly from the fact that a centrifuge was being used for the tests. Restrictions of the side motion that are imposed because of discomfort on a centrifuge, would be imposed by practical design considerations for most other types of motion simulators that operate over a limited travel. The considerations that dictated the washout arrangements in the present studies will, therefore, be found widely applicable in motion simulator studies.

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TABLE I.- PHYSICAL CHARACTERISTICS OF BASIC SIMULATED AIRPLANE

W	300,000 lb	I_x	1,000,000 slug-ft^2
S	4,000 sq ft	I_y	6,000,000 slug-ft^2
b	87 ft	I_z	8,500,000 slug-ft^2
$\bar{c}$	53.6 ft	y_e	27 ft
AR	2.17		

TABLE II.- AERODYNAMIC AND CONTROL CHARACTERISTICS OF BASIC SIMULATED AIRPLANE

C_{L_α}	1.58	C_{n_β}	0.054
$C_{L_{\delta_e}}$	.14	$C_{n_r} - C_{n_{\dot\beta}} \cos \alpha$	-.28
$C_{m_{\delta_e}}$	.21	$C_{n_p} + C_{n_{\dot\beta}} \sin \alpha$	-.0025
C_{m_α}	-.143	$C_{n_{\delta_r}}$	-.0375
$C_{m_q} + C_{m_{\dot\alpha}}$	-2.0	$C_{n_{\delta_a}}$	0
$C_{l_p} + C_{l_{\dot\beta}} \sin \alpha$	-.11	C_{Y_β}	-.50
$C_{l_{\delta_a}}$	-.01	$C_{Y_{\delta_r}}$	.035
$C_{l_r} - C_{l_{\dot\beta}} \cos \alpha$	.028	C_{D_o}	.010
C_{l_β}	-.034	$C_{D_{C_L{}^2}}$	.62
		Static margin	.09

Incremental Aerodynamic Moments and Drag With Stopped Right Outboard Engine[1]

ΔC_l	-0.00034
ΔC_n	.00596
ΔC_m	-.0024
ΔC_D	.0305

Control System Characteristics on 3° and 5° Simulators

Control force gradients (linear)

Elevator	4.6 lb per in. at stick grip, fore and aft
Aileron	2.3 lb per in. at stick grip, side to side
Rudder	18 lb per in. at rudder pedal

Maximum deflection

Elevator (canard)	-0.025 to +0.040 radian
Aileron	±.333 radian (average of right and left)
Rudder	±.072 radian

Control gearing (linear)

Elevator	97.5 inches at stick grip per radian surface deflection
Aileron	13.5 inches at stick grip per radian total surface deflection
Rudder	28.8 inches at pedal per radian surface deflection

[1]Data from reference 4.

TABLE III.- PILOT OPINION RATING SCHEDULE

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No

[1]Failure of a stability augmenter

TABLE IV.- SIMULATION USED TO OBTAIN RATINGS OF EACH PILOT

Cruise Flight at $M = 3$, and 70,000 Feet Altitude

Pilot	Three-degree of-freedom simulation	Five-degree-of-freedom simulation
A	X	X
B	X	X
C	X	X
D	X	
E		X

TABLE V.- COMBINATION OF VALUES SELECTED BY INDIVIDUAL TEST PILOTS FOR A GOOD AND A MARGINALLY SATISFACTORY AIRPLANE IN THREE-DEGREE-OF-FREEDOM SIMULATOR OPERATION

(a) Good Airplane (Pilot Rating 1-1/2)

	Parameter	Pilot A	Pilot B	Pilot C	Pilot D	Basic Airplane PR ≈ 7-8
Lateral-Directional	C_{n_β}	0.081	0.054	0.081	0.129	0.054
	C_{n_r}	-4.20	-4.20	-4.20	-3.40	-.28
	C_{l_β}	-.0063	-.0063	-.0063	-.0085	-.034
	C_{l_p}	-.72	-.72	-.72	-.49	-.11
	$C_{l_{\delta_a}}$	-.025	-.025	-.025	-.010	-.010
	ω_d, radian/sec	1.42	1.17	1.42	1.76	1.13
	ζ_d	.55	.66	.55	.35	.04
	$(\omega_\varphi/\omega_d)^2$	1.0	1.0	1.0	1.0	1.0
	$\lvert\varphi\rvert/\lvert\beta\rvert$	.8	1.2	.8	.6	4.8
	$-1/L_p$, sec	.46	.46	.46	.67	2.99
	$L_{\delta_a}\delta_{a_{max}}$	1.69	1.69	1.69	.68	.68
Longitudinal	C_{m_α}	-.076	-.076	-.076	-.214	-.143
	C_{m_q}	-7.8	-7.8	-7.8	-9.9	-2.0
	$C_{m_{\delta_e}}$	.210	.210	.210	.315	.210
	ω_n	1.34	1.34	1.34	2.17	1.74
	ζ	.61	.61	.61	.47	.15
	$M_{\delta_e}\frac{\delta_e}{\delta_p}$	.03	.03	.03	.09	.03

TABLE V.- COMBINATION OF VALUES SELECTED BY INDIVIDUAL TEST PILOTS FOR A GOOD AND A MARGINALLY SATISFACTORY AIRPLANE IN THREE-DEGREE-OF-FREEDOM SIMULATOR OPERATION - Concluded

(b) Marginally Satisfactory Airplane (Pilot Rating 3-1/2)

	Parameter	Pilot A	Pilot B	Pilot C	Basic Airplane PR ≈ 7-8
Lateral-Directional	C_{n_β}	0.095	0.081	0.081	0.054
	C_{n_r}	-1.75	-1.75	-1.75	-.28
	C_{l_β}	-.015	-.025	-.025	-.034
	C_{l_p}	-.30	-.30	-.30	-.11
	$C_{l_{\delta_a}}$	-.015	-.015	-.015	-.01
	ω_d	1.54	1.44	1.44	1.13
	ζ_d	.24	.24	.24	.04
	$(\omega_\varphi/\omega_d)^2$	1.0	.85	1.00	1.0
	$\lvert\varphi\rvert/\lvert\beta\rvert$	1.2	1.9	1.9	4.8
	$-1/L_p$	1.11	1.11	1.11	2.99
	$L_{\delta_a}\delta_{a_{max}}$	1.02	1.02	1.02	.68
Longitudinal	C_{m_α}	-.143	-.143	-.143	-.143
	C_{m_q}	-4.7	-4.7	-4.7	-2.0
	$C_{m_{\delta_e}}$	.210	.210	.210	.210
	ω_n	1.76	1.76	1.76	1.74
	ζ	.30	.30	.30	.15
	$M_{\delta_e}\frac{\delta_e}{\delta_p}$	.03	.03	.03	.03

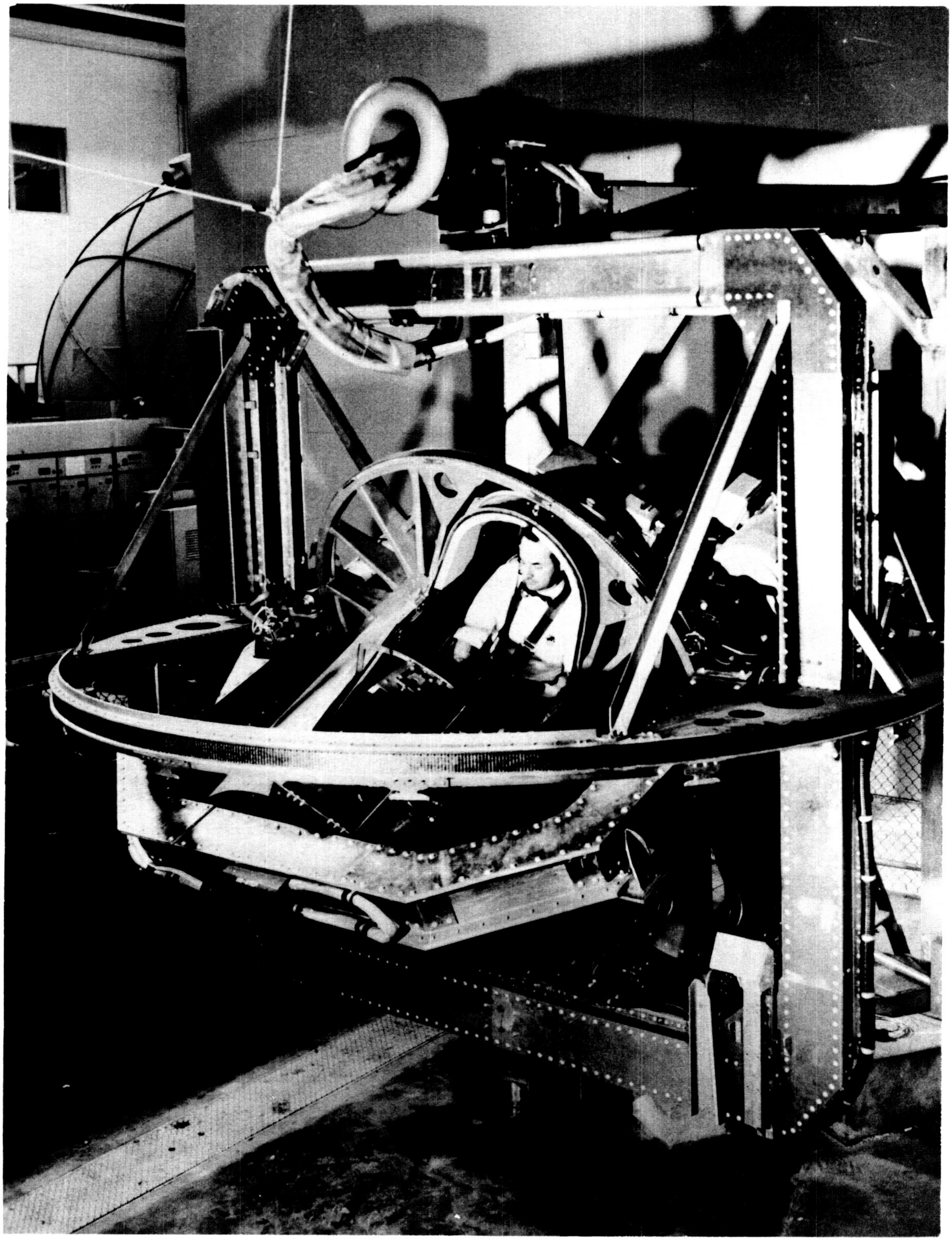

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Figure 1.- Three-degree-of-freedom simulator with cockpit cover removed.

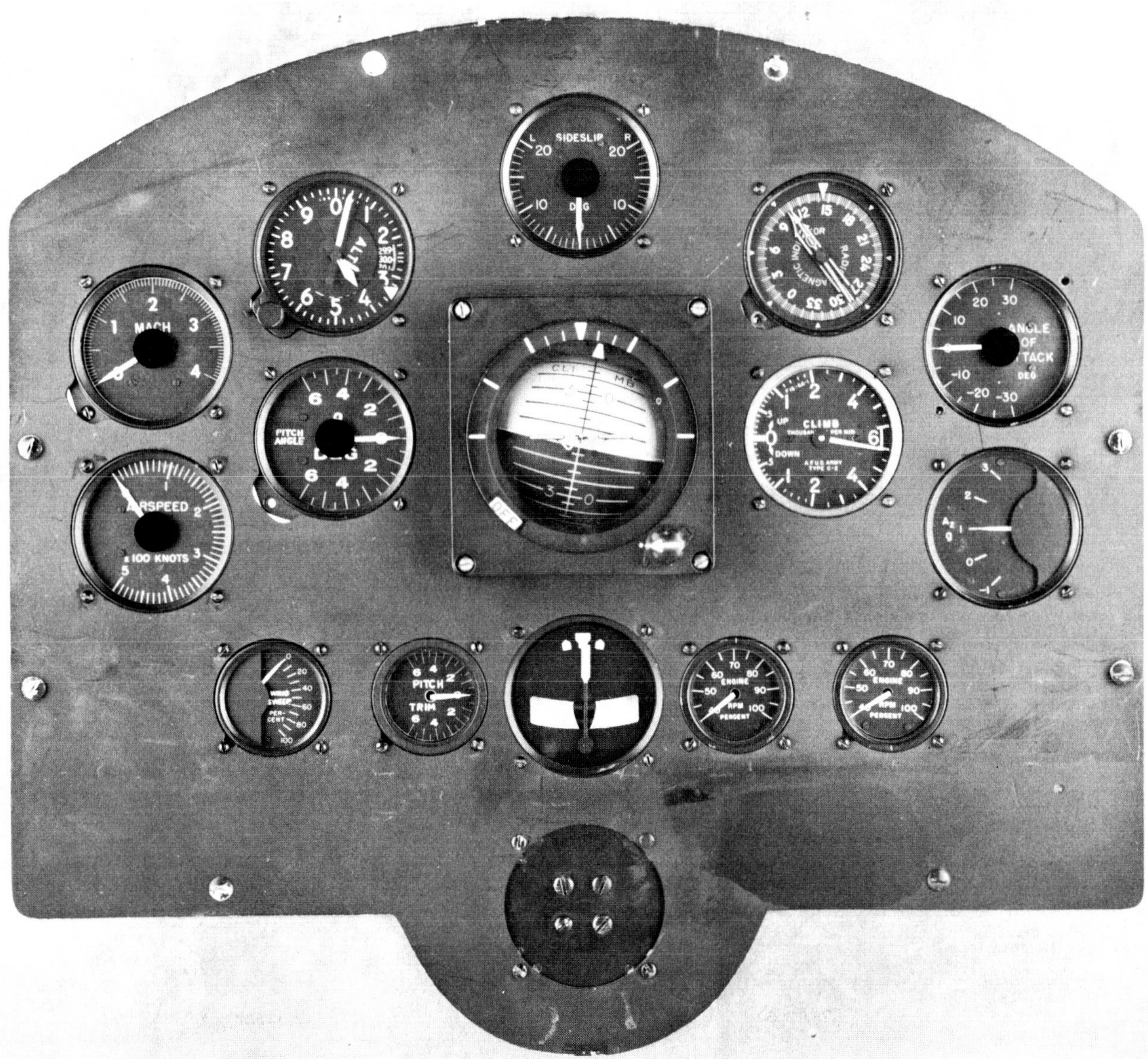

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Figure 2.- Instrument panel of three- and five-degree-of-freedom simulators.

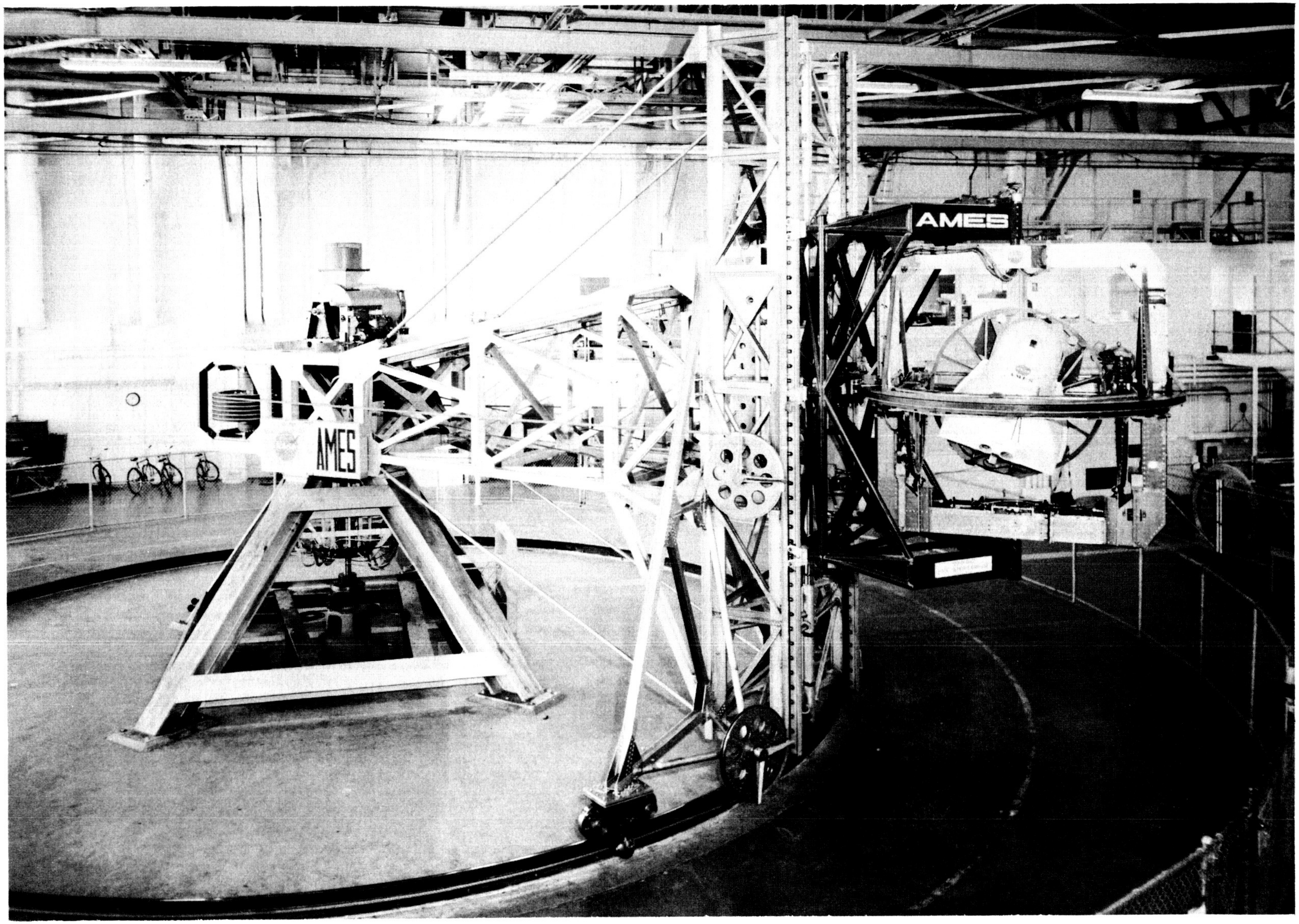

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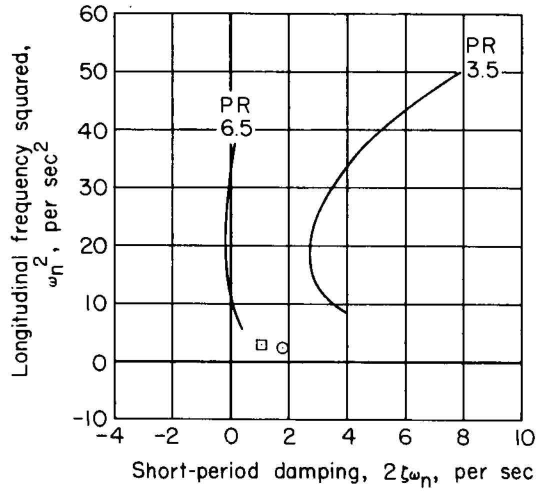
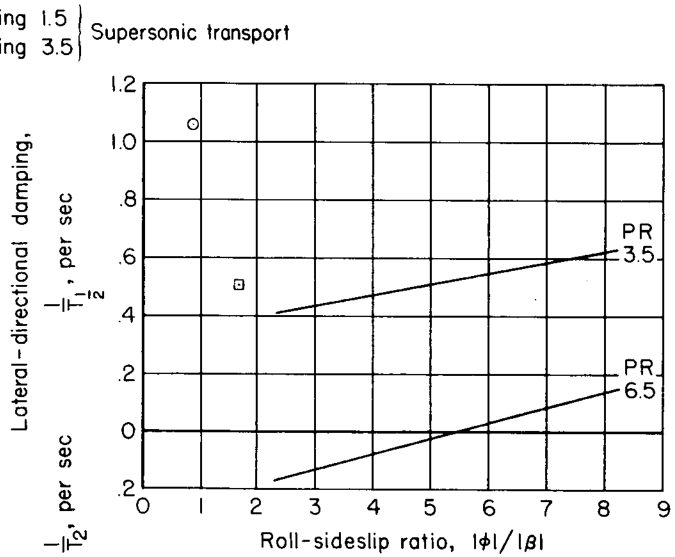
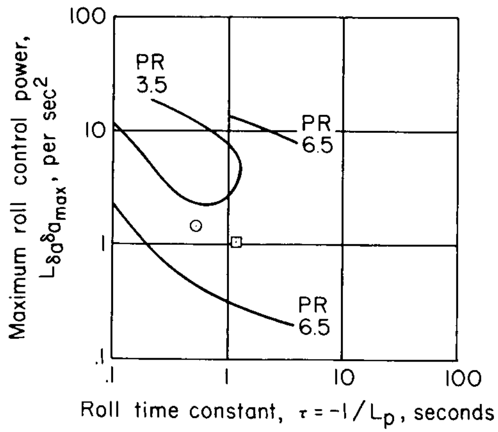
Figure 3.- Five-degree-of-freedom simulator.



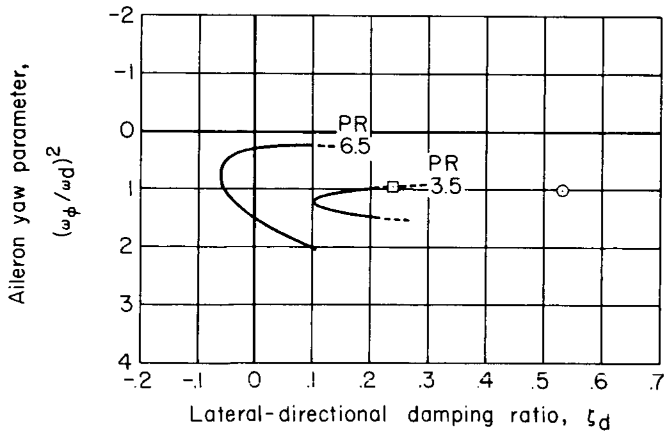
(a) Longitudinal frequency and damping (ref. 9).



(b) Lateral oscillatory characteristics (ref. 11).

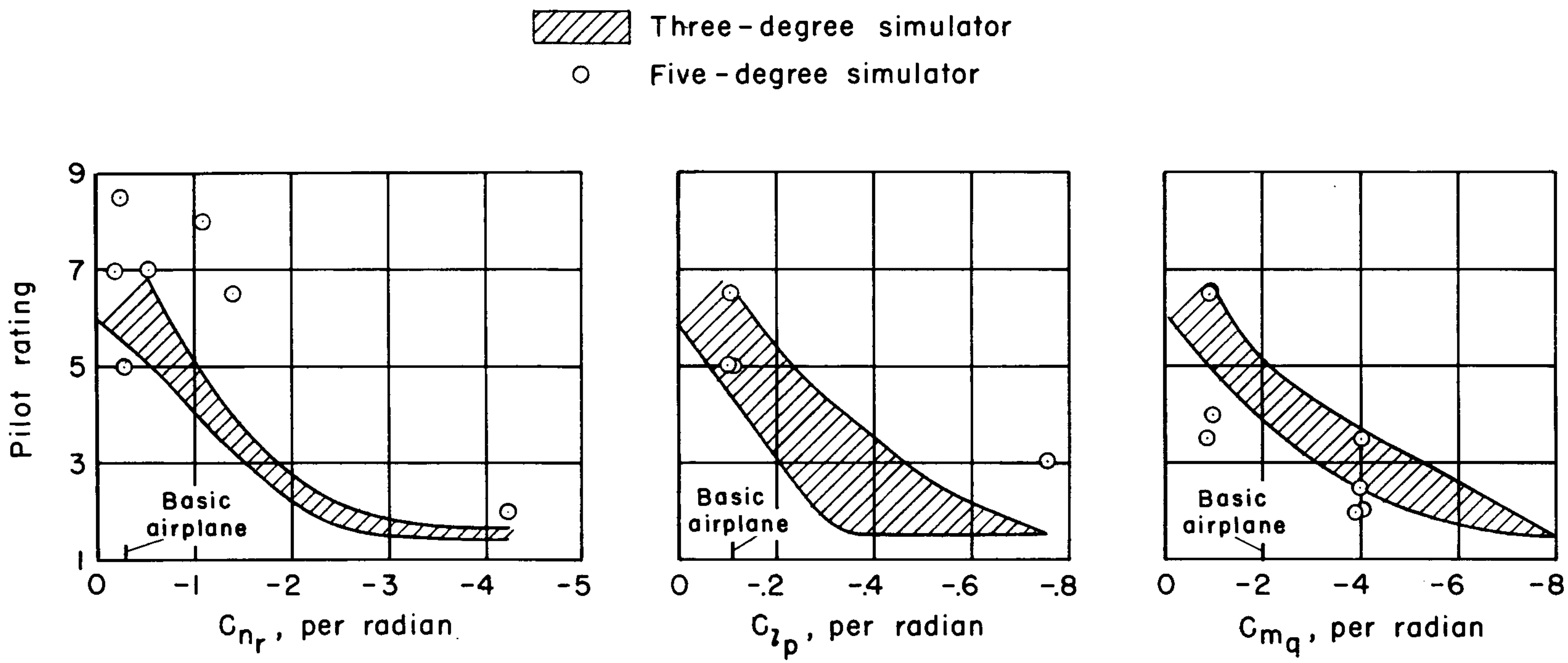


(c) Roll control performance (ref. 12).



(d) Aileron yaw characteristics (ref. 13).

Figure 4.- Comparisons of selected handling-qualities criteria for a good and a marginally satisfactory supersonic transport with boundaries determined in other investigations.

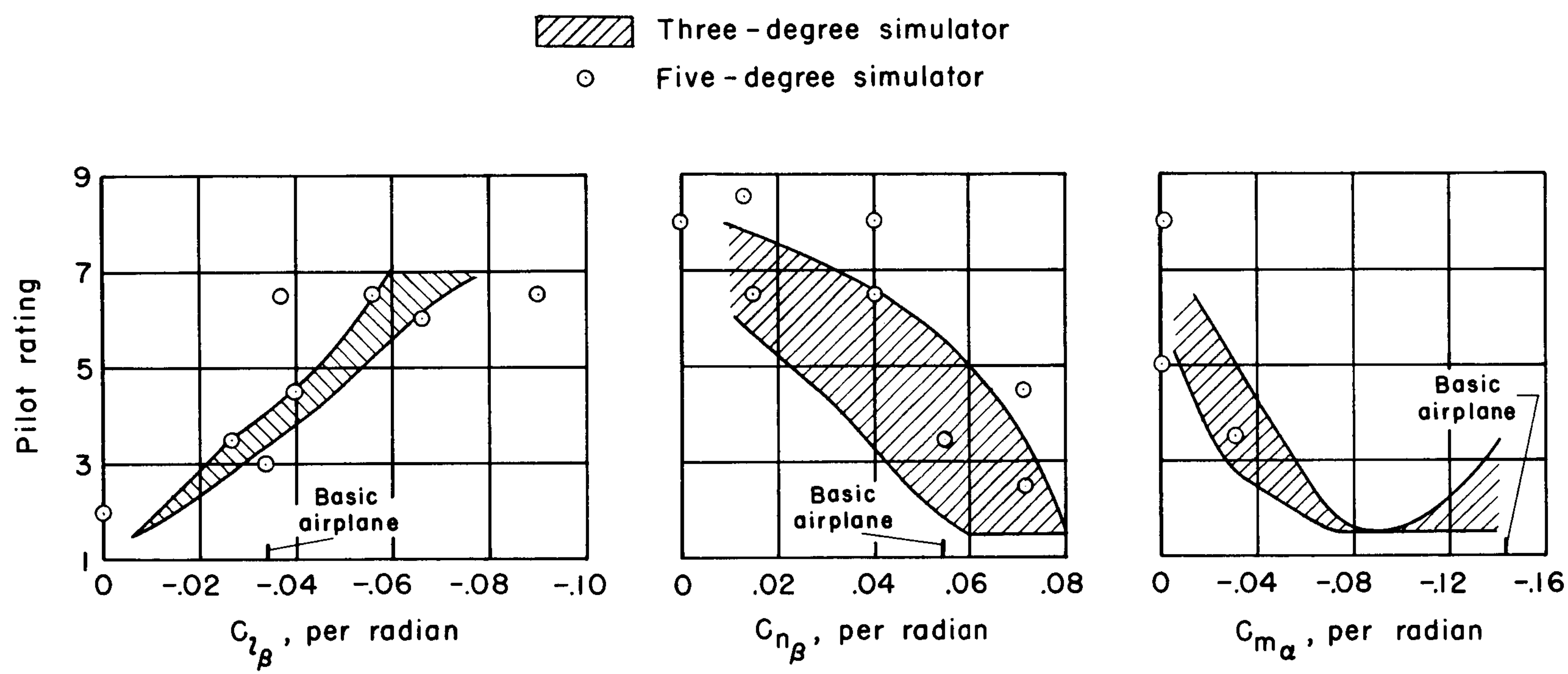


(a) Damping in yaw.

(b) Damping in roll.

(c) Damping in pitch.

Figure 5.- Effect of variations in stability derivatives on pilots' ratings of handling characteristics in cruising flight. Values for each curve determined with all other derivatives set for PR = 1-1/2. Damping derivatives varied.



(a) Dihedral effect. (b) Directional stability. (c) Longitudinal stability.

Figure 6.- Effect of variations in stability derivatives on pilots' ratings of handling characteristics in cruising flight. Values for each curve determined with all other derivatives set for PR = 1-1/2. Static stability derivatives varied.

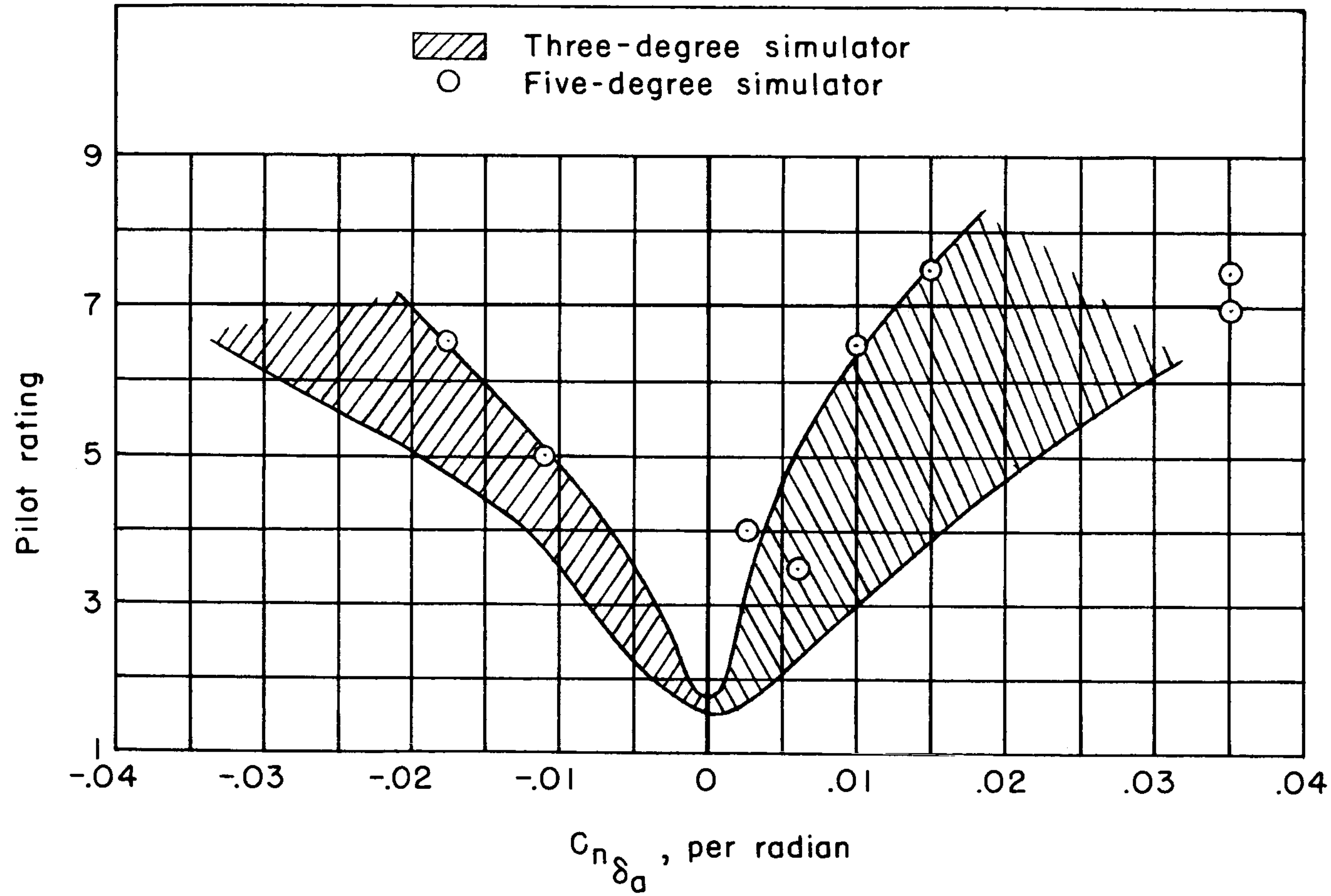


Figure 7.- Effect of variation of aileron yaw derivative on pilots' ratings of handling characteristics in cruising flight. Values determined with all other derivatives set for PR = 1-1/2.

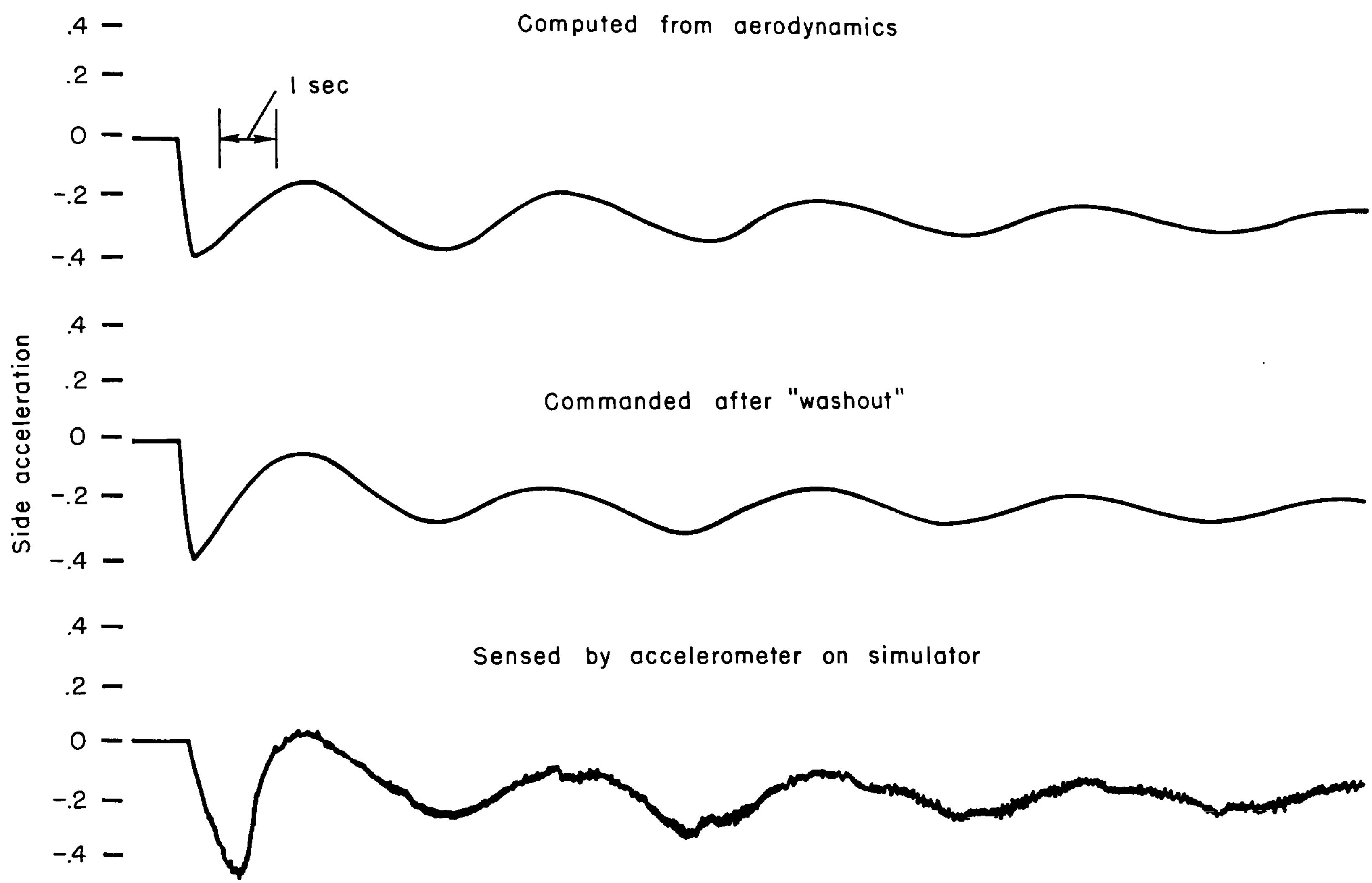


Figure 8.- Time history showing relationship of actual and commanded side acceleration at pilots' compartment following an uncontrolled engine failure; five-degree-of-freedom simulator.